In addition to measuring the weight of an occupying item on a seat, the location of the seat and setback can also be determined by the interrogator. Since the SAW devices inherently create a delayed return signal, either that delay must be very accurately known or an alternate approach is required. One such alternate approach is to use the heterodyne principal described above to cause the antenna to return a signal of a different frequency. By comparing the phases of the sending and received signal, the distance to the device can be determined. Also, as discussed above, multiple antennas can be used for seat position and seatback position sensing.

With respect to switches, devices based on RFID technology can be used as switches in a vehicle as described in U.S. Pat. Nos. 6,078,252 and 6,144,288, and U.S. provisional patent application Ser. No. 60/231,378 all of which are incorporated by reference herein. There are many ways that it can be accomplished. A switch can be used to connect an antenna to either an RFID electronic device or to an RFID SAW device. This of course requires contacts to the closed by the switch activation. An alternate approach is to use pressure from an occupant's finger, for example, to alter the properties of the acoustic wave on the SAW material much as in a SAW touch screen. These properties that can be modified include the amplitude of the acoustic wave, and its phase, and/or the time delay or an external impedance connected to one of the SAW reflectors as disclosed in U.S. Pat. No. 6,084,503, incorporated by reference herein. In this implementation, the SAW transducer can contain two sections, one which is modified by the occupant and the other which serves as a reference. A combined signal is sent to the interrogator that decodes the signal to determine that the switch has been activated. By any of these technologies, switches can be arbitrarily placed within the interior of an automobile, for example, without the need for wires. (The wires would be an optional feature.) Since wires and connectors are the clause of most warranty repairs in an automobile, not only is the cost of switches substantially reduced but also the reliability of the vehicle electrical system is substantially improved.

The interrogation of switches can take place with moderate frequency such as once every 100 milliseconds. Either through the use of different frequencies or different delays, a large number of switches can be either time, code, space or frequency multiplexed to permit separation of the signals obtained by the interrogator.

Another approach is to attach a variable impedance device across one of the reflectors on the SAW device. The impedance can therefore used to determine the relative reflection from the reflector compared to other reflectors on the SAW device. In this way, the magnitude as well as the presence of a force exerted by an occupant's finger, for example, can be used to provide a rate sensitivity to the desired function. In an alternate design, as shown U.S. Pat. No. 6,144,288, incorporated by reference herein, the switch is used to connect the antenna to the SAW device. Of course, in this case the interrogator will not get a return from the SAW switch unless it is depressed.

Temperature measurement is another field in which SAW technology can be applied and the invention encompasses several embodiments of SAW temperature sensors.

U.S. Pat. No. 4,249,418, incorporated by reference herein, is one of many examples of prior art SAW temperature sensors. Temperature sensors are commonly used within vehicles and many more applications might exist if a low cost wireless temperature sensor is available, i.e., the invention. The SAW technology can be used for such temperature sensing tasks. These tasks include measuring the vehicle coolant temperature, air temperature within passenger compartment at multiple locations, seat temperature for use in conjunction with seat warming and cooling systems, outside temperatures and perhaps tire surface temperatures to provide early warning to operators of road freezing conditions. One example, is to provide air temperature sensors in the passenger compartment in the vicinity of ultrasonic transducers used in occupant sensing systems as described in the current assignee's U.S. Pat. No. 5,943,295 (Varga et al.), incorporated by reference herein, since the speed of sound in the air varies by approximately 20% from –40° C. to 85° C. The subject matter of this patent is included in the invention to form part thereof. Current ultrasonic occupant sensor systems do not measure or compensate for this change in the speed of sound with the effect of significantly reducing the accuracy of the systems at the temperature extremes. Through the judicious placement of SAW temperature sensors in the vehicle, the passenger compartment air temperature can be accurately estimated and the information provided wirelessly to the ultrasonic occupant sensor system thereby permitting corrections to be made for the change in speed of sound.

Acceleration sensing is another field in which SAW technology can be applied and the invention encompasses several embodiments of SAW accelerometers.

U.S. Pat. Nos. 4,199,990, 4,306,456 and 4,549,436, all of which are incorporated by reference herein, are examples of prior art SAW accelerometers. Most airbag crash sensors for determining whether the vehicle is experiencing a frontal or side impact currently use micromachined accelerometers. These accelerometers are usually based on the deflection of a mass which is sensed using either capacitive or piezoresistive technologies. SAW technology has heretofore not been used as a vehicle accelerometer or for vehicle crash sensing. Due to the importance of this function, at least one interrogator could be dedicated to this critical function. Acceleration signals from the crash sensors should be reported at least preferably every 100 microseconds. In this case, the dedicated interrogator would send an interrogation pulse to all crash sensor accelerometers every 100 microseconds and receive staggered acceleration responses from each of the SAW accelerometers wirelessly. This technology permits the placement of multiple low-cost accelerometers at ideal locations for crash sensing including inside the vehicle side doors, in the passenger compartment and in the frontal crush zone. Additionally crash sensors can now be located in the rear of the vehicle in the crush zone to sense rear impacts. Since the acceleration data is transmitted wirelessly, concern about the detachment or cutting of wires from the sensors disappears. One of the main concerns, for example, of placing crash sensors in the vehicle doors where they most appropriately can sense vehicle side impacts, is the fear that an impact into the A-pillar of the automobile would sever the wires from the door-mounted crash sensor before the crash was sensed. This problem disappears with the current wireless technology of this invention. If two accelerometers are placed at some distance from each other, the roll rate of the vehicle can be determined and thus the tendency of the vehicle to rollover can be predicted in time to automatically take corrective action and/or deploy a curtain airbag or other airbag(s).

Although the sensitivity of measurement is considerably greater than that obtained with conventional piezo-electric accelerometers, the frequency deviation remains low in absolute value. Accordingly, the frequency drift of thermal origin has to be made as low as possible by selecting a

suitable cut of the piezoelectric material. The resulting accuracy is impressive as presented in U.S. Pat. No. 4,549, 436, incorporated by reference herein, which discloses an angular accelerometer with a dynamic a range of 1 million, temperature coefficient of 0.005%/deg F., an accuracy of 1 microradian/sec^2, a power consumption of 1 milliwatt, a drift of 0.01% per year, a volume of 1 cc/axis and a frequency response of 0 to 1000 Hz. The subject matter of this patent is hereby included in the invention to constitute a part of the invention. A similar design can be used for acceleration sensing.

In a similar manner as the polymer coated SAW device is used to measure pressure, a similar device wherein a seismic mass is attached to a SAW device through a polymer interface can be made to sense acceleration. This geometry has a particular advantage for sensing accelerations below 1 G, which has proved to be very difficult in conventional micromachined accelerometers due to their inability to both measure low accelerations and withstand shocks.

Gyroscopes are another field in which SAW technology can be applied and the invention encompasses several embodiments of SAW gyroscopes.

The SAW technology is particularly applicable for gyroscopes as described in International Publication No. WO 00/79217A2 to Varadan et al. The output of such gyroscopes can be determined with an interrogator that is also used for the crash sensor accelerometers, or a dedicated interrogator can be used. Gyroscopes having an accuracy of approximately 1 degree per second have many applications in a vehicle including skid control and other dynamic stability functions. Additionally, gyroscopes of similar accuracy can be used to sense impending vehicle rollover situations in time to take corrective action.

SAW gyroscopes of the type described in WO 00/79217A2 have the capability of achieving accuracies approaching 3 degrees per hour. This high accuracy permits use of such gyroscopes in an inertial measuring unit (IMU) that can be used with accurate vehicle navigation systems and autonomous vehicle control based on differential GPS corrections. Such a system is described in the current assignee's U.S. patent application Ser. No. 09/177,041. Such navigation systems depend on the availability of four or more GPS satellites and an accurate differential correction signal such as provided by the OmniStar Corporation or NASA or through the National Differential GPS system now being deployed. The availability of these signals degrades in urban canyon environments, tunnels, and on highways when the vehicle is in the vicinity of large trucks. For this application, an IMU system should be able to accurately control the vehicle for perhaps 15 seconds and preferably for up to five minutes. An IMU based on SAW technology or the technology of U.S. Pat. No. 4,549,436 discussed above are the best-known devices capable of providing sufficient accuracies for this application at a reasonable cost. Other accurate gyroscope technologies such as fiber optic systems are more accurate but can cost many thousands of dollars. In contrast, in high volume production, an IMU of the required accuracy based on SAW technology should cost less than $100.

Once an IMU of the accuracy described above is available in the vehicle, this same device can be used to provide significant improvements to vehicle stability control and rollover prediction systems.

Keyless entry systems are another field in which SAW technology can be applied and the invention encompasses several embodiments of access control systems using SAW devices.

A common use of SAW technology is for access control to buildings. RFID technology using electronics is also applicable for this purpose; however, the range of electronic RFID technology is usually limited to one meter or less. In contrast, the SAW technology can permit sensing up to about 30 meters. As a keyless entry system, an automobile can be configured such that the doors unlock as the holder of a card containing the SAW ID system approaches the vehicle and similarly, the vehicle doors can be automatically locked when occupant with the card travels beyond a certain distance from the vehicle. When the occupant enters the vehicle, the doors can again automatically lock either through logic or through a current system wherein doors automatically lock when the vehicle is placed in gear. An occupant with such a card would also not need to have an ignition key. The vehicle would recognize that the SAW based card was inside vehicle and then permit the vehicle to be started by issuing an oral command if a voice recognition system is present or by depressing a button, for example, without the need for an ignition key.

Occupant presence and position sensing is another field in which SAW technology can be applied and the invention encompasses several embodiments of SAW occupant presence and/or position sensors.

Many sensing systems are available for the use to identify and locate occupants or other objects in a passenger compartment of the vehicle. Such sensors include ultrasonic sensors, chemical sensors (e.g. carbon dioxide), cameras, radar systems, heat sensors, capacitance, magnetic or other field change sensors, etc. Most of these sensors require power to operate and return information to a central processor for analysis. An ultrasonic sensor, for example, may be mounted in or near the headliner of the vehicle and periodically it transmits a few ultrasonic waves and receives reflections of these waves from occupying items of the passenger seat. Current systems on the market are controlled by electronics in a dedicated ECU.

An alternate method as taught in this invention is to use an interrogator to send a signal to the headliner-mounted ultrasonic sensor causing that sensor to transmit and receive ultrasonic waves. The sensor in this case would perform mathematical operations on the received waves and create a vector of data containing perhaps twenty to forty values and transmit that vector wirelessly to the interrogator. By means of this system, the ultrasonic sensor need only be connected to the vehicle power system and the information could be transferred to and from the sensor wirelessly. Such a system significantly reduces the wiring complexity especially when there may be multiple such sensors distributed in the passenger compartment. Now, only a power wire needs to be attached to the sensor and there does not need to be any direct connection between the sensor and the control module. Naturally, the same philosophy would apply to radar-based sensors, electromagnetic sensors of all kinds including cameras, capacitive or other electromagnetic field change sensitive sensors etc. In some cases, the sensor itself can operate on power supplied by the interrogator through radio frequency transmission. In this case, even the connection to the power line can be omitted. This principle can be extended to the large number of sensors and actuators that are currently in the vehicle where the only wires that are needed are those to supply power to the sensors and actuators and the information is supplied wirelessly.

Such wireless powerless sensors can also be use, for example, as close proximity sensors based on measurement of thermal radiation from an occupant. Such sensors can be mounted on any of the surfaces in the passenger compartment, including the seats, which are likely to receive such radiation.

A significant number of people are suffocated each year in automobiles due to excessive heat, carbon dioxide, carbon monoxide, or other dangerous fumes. The SAW sensor technology is particularly applicable to solving these kinds of problems. The temperature measurement capabilities of SAW transducers have been discussed above. If the surface of a SAW device is covered with a material which captures carbon dioxide, for example, such that the mass, elastic constants or other property of surface coating changes, the characteristics of the surface acoustic waves can be modified as described in detail in U.S. Pat. No. 4,637,987 and elsewhere. Once again, an interrogator can sense the condition of these chemical-sensing sensors without the need to supply power and connect the sensors with either wireless communication or through the power wires. If a concentration of carbon monoxide is sensed, for example, an alarm can be sounded, the windows opened, and/or the engine extinguished. Similarly, if the temperature within the passenger compartment exceeds a certain level, the windows can be automatically opened a little to permit an exchange of air reducing the inside temperature and thereby perhaps saving the life of an infant or pet left in the vehicle unattended.

In a similar manner, the coating of the surface wave device can contain a chemical which is responsive to the presence of alcohol. In this case, the vehicle can be prevented from operating when the concentration of alcohol vapors in the vehicle exceeds some determined limit.

Each year a number of children and animals are killed when they are locked into a vehicle trunk. Since children and animals emit significant amounts of carbon dioxide, a carbon dioxide sensor connected to the vehicle system wirelessly and powerlessly provides an economic way of detecting the presence of a life form in the trunk. If a life form is detected, then a control system can release a trunk lock thereby opening the trunk. Alarms can also be sounded or activated when a life form is detected in the trunk.

Although they will not be discussed in detail, SAW sensors operating in the wireless mode can also be used to sense for ice on the windshield or other exterior surfaces of the vehicle, condensation on the inside of the windshield or other interior surfaces, rain sensing, heat load sensing and many other automotive sensing functions. They can also be used to sense outside environmental properties and states including temperature, humidity, etc.

SAW sensors can be economically used to measure the temperature and humidity at numerous places both inside and outside of a vehicle. When used to measure humidity inside the vehicle, a source of water vapor can be activated to increase the humanity when desirable and the air conditioning system can be activated to reduce the humidity when necessary. Temperature and humidity measurements outside of the vehicle can be an indication of potential road icing problems. Such information can be used to provide early warning to a driver of potentially dangerous conditions. Although the invention described herein is related to land vehicles, many of these advances are equally applicable to other vehicles such as boats, airplanes and even, in some cases, homes and buildings. The invention disclosed herein, therefore, is not limited to automobiles or other land vehicles.

Road condition sensing is another field in which SAW technology can be applied and the invention encompasses several embodiments of SAW road condition sensors.

The temperature and moisture content of the surface of a roadway are critical parameters in determining the icing state of the roadway. Attempts have been made to measure the coefficient of friction between a tire and the roadway by placing strain gages in the tire tread. Naturally, such strain gages are ideal for the application of SAW technology especially since they can be interrogated wirelessly from a distance and they require no power for operation. As discussed above, SAW accelerometers can also perform this function. The measurement of the friction coefficient, however, is not predictive and the vehicle operator is only able to ascertain the condition after the fact. SAW based transducers have the capability of being interrogated as much as 100 feet from the interrogator. Therefore, the judicious placement of low-cost powerless SAW temperature and humidity sensors in or on the roadway at critical positions can provide an advance warning to vehicle operators that road is slippery ahead. Such devices are very inexpensive and therefore could be placed at frequent intervals along a highway.

An infrared sensor that looks down the highway in front of the vehicle can actually measure the road temperature prior to the vehicle traveling on that part of the roadway. This system also would not give sufficient warning if the operator waited for the occurrence of a frozen roadway. The probability of the roadway becoming frozen, on the other hand, can be predicted long before it occurs, in most cases, by watching the trend in the temperature.

Some lateral control of the vehicle can also be obtained from SAW transducers or electronic RFID tags placed down the center of the lane, either above the vehicles or in the roadway, for example. A vehicle having two receiving antennas approaching such devices, through triangulation, is able to determine the lateral location of the vehicle relative to these SAW devices. If the vehicle also has an accurate map of the roadway, the identification number associated with each such device can be used to obtain highly accurate longitudinal position determinations. Ultimately, the SAW devices can be placed on structures beside the road and perhaps on every mile or tenth of a mile marker. If three antennas are used, as discussed herein, the distances to the SAW device can be determined.

Electronic RFID tags are also suitable for lateral and longitudinal positioning purposes, however, the range available for electronic RFID systems is considerably less than that of SAW based systems. On the other hand, as taught in U.S. provisional patent application Ser. No. 60/231,378, the time of flight of the RFID system can be used to determine the distance from the vehicle to the RFID tag. Because of the inherent delay in the SAW devices and its variation with temperature, accurate distance measurement is probably not practical based on time of flight but somewhat less accurate distance measurements based on relative time of arrival can be made. Even if the exact delay imposed by the SAW device was accurately known at one temperature, such devices are usually reasonably sensitive to changes in temperature, hence they make good temperature sensors, and thus the accuracy of the delay in the SAW device is more difficult to maintain. An interesting variation of an electronic RFID that is particularly applicable to this and other applications of this invention is disclosed in A. Pohl, L. Reindl, "New passive sensors", Proc. 16th IEEE Instrumentation and Measurement Technology Conf., IMTC/99, 1999, pp. 1251–1255. which is incorporated by reference herein in its entirety.

Many SAW devices are based on lithium niobate or similar strong piezoelectric materials. Such materials have high thermal expansion coefficients. An alternate material is quartz that has a very low thermal expansion coefficient. However, its piezoelectric properties are inferior to lithium

niobate. One solution to this problem is to use lithium niobate as the coupling system between the antenna and the material upon which the surface acoustic wave travels. In this matter, the advantages of a low thermal expansion coefficient material can be obtained while using the lithium niobate for its strong piezoelectric properties. Other useful materials such as Langasite have properties that are intermediate between lithium niobate and quartz. Note that it is also possible to use combinations of materials to achieve particular objectives with property measurement since different materials respond differently to different sensed properties or environments.

The use of SAW tags as an accurate precise positioning system as described above would be applicable for accurate vehicle location, as discussed in U.S. patent application Ser. No. 09/177,041, for lanes in tunnels, for example, or other cases where loss of satellite lock is common.

The various technologies discussed above can be used in combination. The electronic RFID tag can be incorporated into a SAW tag providing a single device that provides both an instant reflection of the radio frequency waves as well as a re-transmission at a later time. This marriage of the two technologies permits the strengths of each technology to be exploited in the same device. For most of the applications described herein, the cost of mounting such a tag in a vehicle or on the roadway far exceeds the cost of the tag itself Therefore, combining the two technologies does not significantly affect the cost of implementing tags onto vehicles or roadways or side structures.

An alternate method to the electronic RFID tag is to simply use a radar reflector and measure the time of flight to the reflector and back. The radar reflector can even be made of a series of reflecting surfaces displaced from each other to achieve some simple coding.

Another field in which SAW technology can be applied is for "ultrasound-on-a-surface" type of devices.

U.S. Pat. No. 5,629,681, assigned to the same assignee herein and incorporated by reference herein, describes many uses of ultrasound in a tube. Many of the applications are also candidates for ultrasound-on-a-surface devices. In this case, a micromachined SAW device will in general be replaced by a much larger structure.

Touch screens based on surface acoustic waves are well known in the art. The use of this technology for a touch pad for use with a heads-up display is disclosed in the current assignee's U.S. patent application Ser. No. 09/645,709. The use of surface acoustic waves in either one or two dimensional applications has many other possible uses such as for pinch protection on window and door closing systems, crush sensing crash sensors, occupant presence detector and butt print measurement systems, generalized switches such as on the circumference or center of the steering wheel, etc. Since these devices typically require significantly more power than the micromachined SAW devices discussed above, most of these applications will require a power connection. On the other hand, the output of these devices can go through a SAW micromachined device or, in some other manner, be attached to an antenna and interrogated using a remote interrogator thus eliminating the need for a direct wire communication link.

One example would be to place a surface acoustic wave device on the circumference of the steering wheel. Upon depressing a section of this device, the SAW wave would be attenuated. The interrogator would notify the acoustic wave device at one end of the device to launch an acoustic wave and then monitor output from the antenna. Depending on the phase, time delay, and/or amplitude of the output wave, the interrogator would know where the operator had depressed the steering wheel SAW switch and therefore know the function desired by the operator.

Piezoelectric generators are another field in which SAW technology can be applied and the invention encompasses several embodiments of SAW piezoelectric generators.

An alternate approach for some applications, such as tire monitoring, where it is difficult to interrogate the SAW device as the wheel, and thus the antenna, is rotating, the transmitting power can be significantly increased if there is a source of energy inside the tire. Many systems now use a battery but this leads to problems related to having to periodically replace the battery and temperature effects. In some cases, the manufacturers recommend that the battery be replaced as often as every 6 to 12 months. Batteries also sometimes fail to function properly at cold temperatures and have their life reduced when operated at high temperatures. For these reasons, there is a strong belief that a tire monitoring system should obtain its power from some source external of the tire. Similar problems can be expected for other applications.

One novel solution to this problem is to use the flexing of the tire itself to generate electricity. If a thin film of PVDF is attached to the tire inside and adjacent to the tread, then as the tire rotates the film will flex and generate electricity. This energy can then be stored on one or more capacitors and used to power the tire monitoring circuitry. Also, since the amount of energy that is generated depends of the flexure of the tire, this generator can also be used to monitor the health of the tire in a similar manner as the generation **3** accelerometer system described above.

As mentioned above, the transmissions from different SAW devices can be time multiplexed by varying the delay time from device to device, frequency multiplexed by varying the natural frequencies of the SAW devices, code multiplexed by varying the identification code of the SAW devices or space multiplexed by using multiple antennas. Considering the time multiplexing case, varying the length of the SAW device and thus the delay before retransmission can separate different classes of devices. All seat sensors can have one delay which would be different from tire monitors or light switches etc.

Referring now to FIGS. **13**A–**36**B, a first embodiment of a valve cap **10** including a tire pressure monitoring system in accordance with the invention is shown generally at **10** in FIG. **13**A. A tire **1** has a protruding, substantially cylindrical valve stem **2** which is shown in a partial cutaway view in FIG. **13**A. The valve stem **2** comprises a sleeve **3** and a tire valve assembly **5**. The sleeve **3** of the valve stem **2** is threaded on both its inner surface and its outer surface. The tire valve assembly **5** is arranged in the sleeve **3** and includes threads on an outer surface which are mated with the threads on the inner surface of the sleeve **3**. The valve assembly **5** comprises a valve seat **4** and a valve pin **6** arranged in an aperture in the valve seat **4**. The valve assembly **5** is shown in the open condition in FIG. **13**A whereby air flows through a passage between the valve seat **4** and the valve pin **6**.

The valve cap **10** includes a substantially cylindrical body **9** and is attached to the valve stem **2** by means of threads **8** arranged on an inner cylindrical surface of body **9** which are mated with the threads on the outer surface of the sleeve **3**. The valve cap **10** comprises a valve pin depressor **14** arranged in connection with the body **9** and a SAW pressure sensor **11**. The valve pin depressor **14** engages the valve pin **6** upon attachment of the valve cap **10** to the valve stem **2** and depresses it against its biasing spring, not shown, thereby opening the passage between the valve seat **4** and the

valve pin **6** allowing air to pass from the interior of tire **1** into a reservoir or chamber **12** in the body **9**. Chamber **12** contains the SAW pressure sensor **111** as described in more detail below.

Pressure sensor **11** is an absolute pressure-measuring device. It functions based on the principle that the increase in air pressure and thus air density in the chamber **12** increases the mass loading on a SAW device changing the velocity of surface acoustic wave on the piezoelectric material. The pressure sensor **11** is therefore positioned in an exposed position in the chamber **12**.

A second embodiment of a valve cap **10**' in accordance with the invention is shown in FIG. **13**B and comprises a SAW strain sensing device **15** that is mounted onto a flexible membrane **13** attached to the body **9**' of the valve cap **10**' and in a position in which it is exposed to the air in the chamber **12**'. When the pressure changes in chamber **12**', the deflection of the membrane **13** changes thereby changing the stress in the SAW device **15**.

Strain sensor **15** is thus a differential pressure-measuring device. It functions based on the principle that changes in the flexure of the membrane **13** can be correlated to changes in pressure in the chamber **12**' and thus, if an initial pressure and flexure are known, the change in pressure can be determined from the change in flexure.

FIGS. **13**A and **13**B therefore illustrate two different methods of using a SAW sensor in a valve cap for monitoring the pressure inside a tire. The precise manner in which the SAW sensors **11**,**15** operate is discussed fully below but briefly, each sensor **11**,**15** includes an antenna and an interdigital transducer which receives a wave via the antenna from an interrogator which proceeds to travel along a substrate. The time in which the waves travel across the substrate and return to the interdigital transducer is dependent on the temperature, the mass loading on the substrate (in the embodiment of FIG. **13**A) or the flexure of membrane **13** (in the embodiment of FIG. **13**B). The antenna transmits a return wave which is receives and the time delay between the transmitted and returned wave is calculated and correlated to the pressure in the chamber **12** or **12**'.

Sensors **11** and **15** are electrically connected to the metal valve cap **10** that is electrically connected to the valve stem **2**. The valve stem **2** is electrically isolated from the tire rim and serves as an antenna for transmitting radio frequency electromagnetic signals from the sensors **11** and **15** to a vehicle mounted interrogator, not shown, to be described in detail below. As shown in FIG. **13**A., a pressure seal **16** is arranged between an upper rim of the sleeve **3** and an inner shoulder of the body **9** of the valve cap **10** and serves to prevent air from flowing out of the tire **1** to the atmosphere.

The speed of the surface acoustic wave on the piezoelectric substrate changes with temperature in a predictable manner as well as with pressure. For the valve cap implementations, a separate SAW device can be attached to the outside of the valve cap and protected with a cover where it is subjected to the same temperature as the SAW sensors **11** or **15** but is not subject to pressure or strain. This requires that each valve cap comprise two SAW devices, one for pressure sensing and another for temperature sensing. Since the valve cap is exposed to ambient temperature, a preferred approach is to have a single device on the vehicle which measures ambient temperature outside of the vehicle passenger compartment. Many vehicles already have such a temperature sensor. For those installations where access to this temperature data is not convenient, a separate SAW temperature sensor can be mounted associated with the interrogator antenna, as illustrated below, or some other convenient place.

Although the valve cap **10** is provided with the pressure seal **16**, there is a danger that the valve cap **10** will not be properly assembled onto the valve stem **2** and a small quantity of the air will leak over time. FIG. **14** provides an alternate design where the SAW temperature and pressure measuring devices are incorporated into the valve stem. This embodiment is thus particularly useful in the initial manufacture of a tire.

The valve stem assembly is shown generally at **20** and comprises a brass valve stem **7** which contains a tire valve assembly **5**. The valve stem **7** is covered with a coating **21** of a resilient material such as rubber, which has been partially removed in the drawing. A metal conductive ring **22** is electrically attached to the valve stem **7**. A rubber extension **23** is also attached to the lower end of the valve stem **7** and contains a SAW pressure and temperature sensor **24**. The SAW pressure and temperature sensor **24** can be of at least two designs wherein the SAW sensor is used as an absolute pressure sensor as shown in FIG. **14**A or an as a differential sensor based on membrane strain as shown in FIG. **14**B.

In FIG. **14**A, the SAW sensor **24** comprises a capsule **32** having an interior chamber in communication with the interior of the tire via a passageway **30**. A SAW absolute pressure sensor **27** is mounted onto one side of a rigid membrane or separator **31** in the chamber in the capsule **32**. Separator **31** divides the interior chamber of the capsule **32** into two compartments **25** and **26**, with only compartment **25** being in flow communication with the interior of the tire. The SAW absolute pressure sensor **27** is mounted in compartment **25** which is exposed to the pressure in the tire through passageway **30**. A SAW temperature sensor **28** is attached to the other side of the separator **31** and is exposed to the pressure in compartment **26**. The pressure in compartment **26** is unaffected by the tire pressure and is determined by the atmospheric pressure when the device was manufactured and the effect of temperature on this pressure. The speed of sound on the SAW temperature sensor **28** is thus affected by temperature but not by pressure in the tire.

The operation of SAW sensors **27** and **28** is discussed elsewhere more fully but briefly, since SAW sensor **27** is affected by the pressure in the tire, the wave which travels along the substrate is affected by this pressure and the time delay between the transmission and reception of a wave can be correlated to the pressure. Similarly, since SAW sensor **28** is affected by the temperature in the tire, the wave which travels along the substrate is affected by this temperature and the time delay between the transmission and reception of a wave can be correlated to the temperature.

FIG. **14**B illustrates an alternate configuration of sensor **24** where a flexible membrane **33** is used instead of the rigid separator **31** shown in the embodiment of FIG. **14**A, and a SAW device is mounted on flexible member **33**. In this embodiment, the SAW temperature sensor **28** is mounted to a different wall of the capsule **32**. A SAW device **29** is thus affected both by the strain in membrane **33** and the absolute pressure in the tire. Normally, the strain effect will be much larger with a properly designed membrane **33**.

The operation of SAW sensors **28** and **29** is discussed elsewhere more fully but briefly, since SAW sensor **28** is affected by the temperature in the tire, the wave which travels along the substrate is affected by this temperature and the time delay between the transmission and reception of a wave can be correlated to the temperature. Similarly, since SAW sensor **29** is affected by the pressure in the tire, the wave which travels along the substrate is affected by this pressure and the time delay between the transmission and reception of a wave can be correlated to the pressure.

In both of the embodiments shown in FIG. **14**A and FIG. **14**B, a separate temperature sensor is illustrated. This has two advantages. First, it permits the separation of the temperature effect from the pressure effect on the SAW device. Second, it permits a measurement of tire temperature to be recorded. Since a normally inflated tire can experience excessive temperature caused, for example, by an overload condition, it is desirable to have both temperature and pressure measurements of each vehicle tire

The SAW devices **27**, **28** and **29** are electrically attached to the valve stem **7** which again serves as an antenna to transmit radio frequency information to an interrogator. This electrical connection can be made by a wired connection; however, the impedance between the SAW devices and the antenna may not be properly matched.

An alternate approach as described in Varadan, V.K. et al., "Fabrication, characterization and testing of wireless MEMS-IDT based microaccelerometers" Sensors and Actuators A 90 (2001) p. 7–19, 2001 Elsevier Netherlands, incorporated herein by reference, is to inductively couple the SAW devices to the brass tube.

Although an implementation into the valve stem and valve cap examples have been illustrated above, an alternate approach is to mount the SAW temperature and pressure monitoring devices elsewhere within the tire. Similarly, although the tire stem in both cases above serves the antenna, in many implementations, it is preferable to have a separately designed antenna mounted within or outside of the vehicle tire. For example, such an antenna can project into the tire from the valve stem or can be separately attached to the tire or tire rim either inside or outside of the tire. In some cases, it can be mounted on the interior of the tire on the sidewall.

A more advanced embodiment of a tire monitor in accordance with the invention is illustrated generally at **40** in FIGS. **15** and **15**A. In addition to temperature and pressure monitoring devices as described in the previous applications, the tire monitor assembly **40** comprises an accelerometer of any of the types to be described below which is configured to measure either or both of the tangential and radial accelerations. Tangential accelerations as used herein mean accelerations tangent to the direction of rotation of the tire and radial accelerations as used herein mean accelerations toward or away from the wheel axis. For either accelerometer case, the acceleration will be zero when the monitor assembly **40** is closest to the road and will be at a maximum when the monitor assembly **40** is at its maximum distance from the road. Both accelerations will increase and decrease at all positions in between.

In FIG. **15**, the tire monitor assembly **40** is cemented to the interior of the tire opposite the tread. In FIG. **15**A, the tire monitor assembly **40** is inserted into the tire opposite the tread during manufacture.

Superimposed on the acceleration signals will be vibrations introduced into tire from road interactions and due to tread separation and other defects. Additionally, the presence of the nail or other object attached to the tire will, in general, excite vibrations that can be sensed by the accelerometers. When the tread is worn to the extent that the wire belts **41** begin impacting the road, additional vibrations will be induced.

Through monitoring the acceleration signals from the tangential or radial accelerometers within the tire monitor assembly **40**, delamination, a worn tire condition, imbedded nails, other debris attached to the tire tread, hernias, can all be sensed. Additionally, as previously discussed, the length of time that the tire tread is in contact with the road opposite tire monitor **40** can be measured and, through a comparison with the total revolution time, the length of the tire footprint on the road can be determined. This permits the load on the tire to be measured, thus providing an indication of excessive tire loading. As discussed above, a tire can fail due to over loading even when the tire interior temperature and pressure are within acceptable limits. Other tire monitors cannot sense such conditions.

Since the acceleration changes during the rotation of the tire, a simple switch containing an acceleration sensing mass can now be designed that would permit data transmission only during one part of the tire rotation. Such a switch can be designed, for example, such that it shorts out the antenna except when the tire is experiencing zero acceleration at which time it permits the device to transmit data to the interrogator. Such a system would save on battery power, for example, for powered systems and minimize bandwidth use for passive systems.

In the discussion above, the use of the tire valve stem as an antenna has been discussed. An antenna can also be placed within the tire when the tire sidewalls are not reinforced with steel. In some cases and for some frequencies, it is sometimes possible to use the tire steel bead or steel belts as an antenna, which in some cases can be coupled to inductively. Alternately, the antenna can be designed integral with the tire beads or belts and optimized and made part of the tire during manufacture.

Although the discussion above has centered on the use of SAW devices, the configuration of FIG. **15** can also be effectively accomplished with other pressure, temperature and accelerometer sensors. One of the advantages of using SAW devices is that they are totally passive thereby eliminating the requirement of a battery. For the implementation of tire monitor assembly **40**, the changes in acceleration can also be used to generate sufficient electrical energy to power a silicon microcircuit. In this configuration, additional devices, typically piezoelectric devices, are used as a generator of electricity that can be stored in one or more conventional capacitors or ultra-capacitors. Naturally, other types of electrical generators can be used such as those based on a moving coil and a magnetic field etc. A PVDF piezoelectric polymer can also be used to generate electrical energy based on the flexure of the tire as described below.

FIG. **16** illustrates an absolute pressure sensor based on surface acoustic wave (SAW) technology. A SAW absolute pressure sensor **50** has an interdigital transducer (IDT) **51** which is connected to antenna **52**. Upon receiving an RF signal of the proper frequency, the antenna induces a surface acoustic wave in the material **53** which can be lithium niobate, quartz, zinc oxide, or other appropriate piezoelectric material. As the wave passes through a pressure sensing area **54** formed on the material **53**, its velocity is changed depending on the air pressure exerted on the sensing area **54**. The wave is then reflected by reflectors **55** where it returns to the IDT **51** and to the antenna **52** for retransmission back to the interrogator. The material in the pressure sensing area **54** can be a thin (such as one micron) coating of a polymer that absorbs or reversibly reacts with oxygen or nitrogen where the amount absorbed depends on the air density.

In FIG. **16**A, two additional sections of the SAW device, designated **56** and **57**, are provided such that the air pressure affects sections **56** and **57** differently than pressure sensing area **54**. This is achieved by providing three reflectors. The three reflecting areas cause three reflected waves to appear, **59**, **60** and **61** when input wave **62** is provided. The spacing between waves **59** and **60**, and between waves **60** and **61** provides a measure of the pressure. This construction of a

pressure sensor may be utilized in the embodiments of FIGS. **13**A–**15** or in any embodiment wherein a pressure measurement by a SAW device is obtained.

There are many other ways in which the pressure can be measured based on either the time between reflections or on the frequency or phase change of the SAW device as is well known to those skilled in the art. FIG. **16**B, for example, illustrates an alternate SAW geometry where only two sections are required to measure both temperature and pressure. This construction of a temperature and pressure sensor may be utilized in the embodiments of FIGS. **13**A–**15** or in any embodiment wherein both a pressure measurement and a temperature measurement by a single SAW device is obtained.

Another method where the speed of sound on a piezoelectric material can be changed by pressure was first reported in Varadan et al., "Local/Global SAW Sensors for Turbulence" referenced above. This, phenomenon has not been applied to solving pressure sensing problems within an automobile until now. The instant invention is believed to be the first application of this principle to measuring tire pressure, oil pressure, coolant pressure, pressure in a gas tank, etc. Experiments to date, however, have been unsuccessful.

In some cases, a flexible membrane is placed loosely over the SAW device to prevent contaminants from affecting the SAW surface. The flexible membrane permits the pressure to be transferred to the SAW device without subjecting the surface to contaminants. Such a flexible membrane can be used in most if not all of the embodiments described herein.

A SAW temperature sensor **60** is illustrated in FIG. **17**. Since the SAW material, such as lithium niobate, expands significantly with temperature, the natural frequency of the device also changes. Thus, for a SAW temperature sensor to operate, a material for the substrate is selected which changes its properties as a function of temperature, i.e., expands. Similarly, the time delay between the insertion and retransmission of the signal also varies measurably. Since speed of a surface wave is typically 100,000 times slower then the speed of light, usually the time for the electromagnetic wave to travel to the SAW device and back is small in comparison to the time delay of the SAW wave and therefore the temperature is approximately the time delay between transmitting electromagnetic wave and its reception.

An alternate approach as illustrated in FIG. **17**A is to place a thermistor **62** across an interdigital transducer (IDT) **61**, which is now not shorted as it was in FIG. **17**. In this case, the magnitude of the returned pulse varies with the temperature. Thus, this device can be used to obtain two independent temperature measurements, one based on time delay or natural frequency of the device **60** and the other based on the resistance of the thermistor **62**.

When some other property such as pressure is being measured by the device **65** as shown in FIG. **17**B, two parallel SAW devices are commonly used. These devices are designed so that they respond differently to one of the parameters to be measured. Thus, SAW device **66** and SAW device **67** can be designed to both respond to temperature and respond to pressure. However, SAW device **67**, which contains a surface coating, will respond differently to pressure than SAW device **66**. Thus, by measuring natural frequency or the time delay of pulses inserted into both SAW devices **66** and **67**, a determination can be made of both the pressure and temperature, for example. Naturally, the device which is rendered sensitive to pressure in the above discussion could alternately be rendered sensitive to some other property such as the presence or concentration of a gas, vapor, or liquid chemical as described in more detail below.

An accelerometer that can be used for either radial or tangential acceleration in the tire monitor assembly of FIG. **15** is illustrated in FIGS. **18** and **18**A. The design of this accelerometer is explained in detail in Varadan, V. K. et al., "Fabrication, characterization and testing of wireless MEMS-IDT based microaccelerometers" referenced above, which is incorporated in its entirety herein by reference, and will not be repeated herein.

A stud which is threaded on both ends and which can be used to measure the weight of an occupant seat is illustrated in FIGS. **19**A–**19**D. The operation of this device is disclosed in U.S. patent application Ser. No. 09/849,558 wherein the center section of stud **101** is solid. It has been discovered that sensitivity of the device can be significantly improved if a slotted member is used as described in U.S. Pat. No. 5,539,236, which is incorporated herein by reference. FIG. **19**A illustrates a SAW strain gage **102** mounted on a substrate and attached to span a slot **104** in a center section **105** of the stud **101**. This technique can be used with any other strain-measuring device.

FIG. **19**B is a side view of the device of FIG. **19**A.

FIG. **19**C illustrates use of a single hole **106** drilled off-center in the center section **105** of the stud **101**. A single hole **106** also serves to magnify the strain as sensed by the strain gage **102**. It has the advantage in that strain gage **102** does not need to span an open space. The amount of magnification obtained from this design, however, is significantly less than obtained with the design of FIG. **19**A.

To improve the sensitivity of the device shown in FIG. **19**C, multiple smaller holes **107** can be used as illustrated in FIG. **19**D. FIG. **19**E in an alternate configuration showing four gages for determining the bending moments as well as the axial stress in the support member.

In operation, the SAW strain gage **102** receives radio frequency waves from an interrogator **110** and returns electromagnetic waves via a respective antenna **103** which are delayed based on the strain sensed by strain gage **102**.

A SAW device can also be used as a wireless switch as shown in FIGS. **20**A and **20**B. FIG. **20**A shows a surface **120** containing a projection **122** on top of a SAW device **121**. Surface material **120** could be, for example, the armrest of an automobile, the steering wheel airbag cover, or any other surface within the passenger compartment of an automobile or elsewhere. Projection **122** will typically be a material capable of transmitting force to the surface of SAW device **121**. As shown in FIG. **20**B, a projection **123** may be placed on top of the SAW device **124**. This projection **123** permits force exerted on the projection **122** to create a pressure on the SAW device **124**. This increased pressure changes the time delay or natural frequency of the SAW wave traveling on the surface of material. Alternately, it can affect the magnitude of the returned signal. The projection **123** is typically held slightly out of contact with the surface until forced into contact with it.

An alternate approach is to place a switch across the IDT **127** as shown in FIG. **20**C. If switch **125** is open, then the device will not return a signal to the interrogator. If it is closed, than the IDT **127** will act as a reflector sending a single back to IDT **128** and thus to the interrogator. Alternately, a switch **126** can be placed across the SAW device. In this case, a switch closure shorts the SAW device and no signal is returned to the interrogator. For the embodiment of FIG. **20**C, using switch **126** instead of switch **125**, a standard reflector IDT would be used in place of the IDT **127**.

Most SAW-based accelerometers work on the principle of straining the SAW surface and thereby changing either the

time delay or natural frequency of the system. An alternate novel accelerometer is illustrated FIG. **21**A wherein a mass **130** is attached to a silicone rubber coating **131** which has been applied the SAW device. Acceleration of the mass in FIG. **21** in the direction of arrow X changes the amount of rubber in contact with the surface of the SAW device and thereby changes the damping, natural frequency or the time delay of the device. By this method, accurate measurements of acceleration below 1 G are readily obtained. Furthermore, this device can withstand high deceleration shocks without damage. FIG. **21**B illustrates a more conventional approach where the strain in a beam **137** caused by the acceleration acting on a mass **136** is measured with a SAW strain sensor **135**.

It is important to note that all of these devices have a high dynamic range compared with most competitive technologies. In some cases, this dynamic range can exceed 100,000. This is the direct result of the ease with which frequency and phase can be accurately measured.

A gyroscope, which is suitable for automotive applications, is illustrated in FIG. **22** and described in detail in V. K. Varadan's International Application No. WO 00/79217, which is incorporated by reference herein in its entirety. This SAW-based gyroscope has applicability for the vehicle navigation, dynamic control, and rollover sensing among others.

Note that any of the disclosed applications can be interrogated by the central interrogator of this invention and can either be powered or operated powerlessly as described in general above. Block diagrams of three interrogators suitable for use in this invention are illustrated in FIGS. **23**A–**23**C. FIG. **23**A illustrates a superheterodyne circuit and FIG. **23**B illustrates a dual superheterodyne circuit. FIG. **23**C operates as follows. During the burst time two frequencies, F1 and F1+F2, are sent by the transmitter after being generated by mixing using oscillator Osc. The two frequencies are needed by the SAW transducer where they are mixed yielding F2 which is modulated by the SAW and contains the information. Frequency (F1+F2) is sent only during the burst time while frequency F1 remains on until the signal F2 returns from the SAW. This signal is used for mixing. The signal returned from the SAW transducer to the interrogator is F1+F2 where F2 has been modulated by the SAW transducer. It is expected that the mixing operations will result in about 12 db loss in signal strength.

FIG. **24** illustrates a central antenna mounting arrangement for permitting interrogation of the tire monitors for four tires and is similar to that described in U.S. Pat. No. 4,237,728, which is incorporated by reference herein. An antenna package **200** is mounted on the underside of the vehicle and communicates with devices **201** through their antennas as described above. In order to provide for antennas both inside (for example for weight sensor interrogation) and outside of the vehicle, another antenna assembly (not shown) can be mounted on the opposite side of the vehicle floor from the antenna assembly **200**.

FIG. **24**A is a schematic of the vehicle shown in FIG. **24**. The antenna package **200**, which can be considered as an electronics module, contains a time domain multiplexed antenna array that sends and receives data from each of the five tires (including the spare tire), one at a time. It comprises a microstrip or stripline antenna array and a microprocessor on the circuit board. The antennas that face each tire are in an X configuration so that the transmissions to and from the tire can be accomplished regardless of the tire rotation angle.

Based on the frequency and power available, and on FCC limitations, SAW devices can be designed to permit transmission distances of up to 100 feet or more. Since SAW devices can measure both temperature and humidity, they are also capable of monitoring road conditions in front of and around a vehicle. Thus, a properly equipped vehicle can determine the road conditions prior to entering a particular road section if such SAW devices are embedded in the road surface or on mounting structures close to the road surface as shown at **279** in FIG. **25**. Such devices could provide advance warning of freezing conditions, for example. Although at 60 miles per hour, such devices may only provide a one second warning, this can be sufficient to provide information to a driver to prevent dangerous skidding. Additionally, since the actual temperature and humidity can be reported, the driver will be warned prior to freezing of the road surface. SAW device **279** is shown in detail in FIG. **25**A.

If a SAW device **283** is placed in a roadway, as illustrated in FIG. **26**, and if a vehicle **290** has two receiving antennas **280** and **281**, an interrogator can transmit a signal from either of the two antennas and at a later time, the two antennas will receive the transmitted signal from the SAW device. By comparing the arrival time of the two received pulses, the position of vehicle on a lane can precisely determined (since the direction from each antenna **280**,**281** to the SAW device **283** can be calculated). If the SAW device **283** has an identification code encoded into the returned signal generated thereby, then the vehicle **290** can determine, providing a precise map is available, its position on the surface of the earth. If another antenna **286** is provided, for example, at the rear of the vehicle **290** then the longitudinal position of the vehicle can also be accurately determined as the vehicle passes the SAW device **283**. Of course the SAW device **283** need not be in the center of the road. Alternate locations for positioning of the SAW device **283** are on overpasses above the road and on poles such as **284** and **285** on the roadside. Such a system has an advantage over a competing system using radar and reflectors in that it is easier to measure the relative time between the two received pulses than it is to measure time of flight of a radar signal to a reflector and back. Such a system operates in all weather conditions and is known as a precise location system. Eventually such a SAW device **283** can be placed every tenth of a mile along the roadway or at some other appropriate spacing.

If a vehicle is being guided by a DGPS and accurate map system such as disclosed in U.S. patent application Ser. No. 09/679,317 filed Oct. 4, 2000, which is incorporated by reference herein, a problem arises when the GPS receiver system looses satellite lock as would happen when the vehicle enters a tunnel, for example. If a precise location system as described above is placed at the exit of the tunnel then the vehicle will know exactly where it is and can re-establish satellite lock in as little as one second rather than typically 15 seconds as might otherwise be required. Other methods making use of the cell phone system can be used to establish an approximate location of the vehicle suitable for rapid acquisition of satellite lock as described in G. M. Djuknic, R. E. Richton "Geolocation and Assisted GPS", Computer Magazine, February 2001, IEEE Computer Society, which is incorporated by reference herein in its entirety.

More particularly, geolocation technologies that rely exclusively on wireless networks such as time of arrival, time difference of arrival, angle of arrival, timing advance, and multipath fingerprinting offer a shorter time-to-first-fix (TTFF) than GPS. They also offer quick deployment and continuous tracking capability for navigation applications,

without the added complexity and cost of upgrading or replacing any existing GPS receiver in vehicles. Compared to either mobile-station-based, stand-alone GPS or network-based geolocation, assisted-GPS (AGPS) technology offers superior accuracy, availability, and coverage at a reasonable cost. AGPS for use with vehicles would comprise a communications unit with a partial GPS receiver arranged in the vehicle, an AGPS server with a reference GPS receiver that can simultaneously "see" the same satellites as the communications unit, and a wireless network infrastructure consisting of base stations and a mobile switching center. The network can accurately predict the GPS signal the communication unit will receive and convey that information to the mobile, greatly reducing search space size and shortening the TTFF from minutes to a second or less. In addition, an AGPS receiver in the communication unit can detect and demodulate weaker signals than those that conventional GPS receivers require. Because the network performs the location calculations, the communication unit only needs to contain a scaled-down GPS receiver. It is accurate within about 15 meters when they are outdoors, an order of magnitude more sensitive than conventional GPS.

Since an AGPS server can obtain the vehicle's position from the mobile switching center, at least to the level of cell and sector, and at the same time monitor signals from GPS satellites seen by mobile stations, it can predict the signals received by the vehicle for any given time. Specifically, the server can predict the Doppler shift due to satellite motion of GPS signals received by the vehicle, as well as other signal parameters that are a function of the vehicle's location. In a typical sector, uncertainty in a satellite signal's predicted time of arrival at the vehicle is about±5 μs, which corresponds to±5 chips of the GPS coarse acquisition (C/A) code. Therefore, an AGPS server can predict the phase of the pseudorandom noise (PRN) sequence that the receiver should use to despread the C/A signal from a particular satellite—each GPS satellite transmits a unique PRN sequence used for range measurements—and communicate that prediction to the vehicle. The search space for the actual Doppler shift and PRN phase is thus greatly reduced, and the AGPS receiver can accomplish the task in a fraction of the time required by conventional GPS receivers. Further, the AGPS server maintains a connection with the vehicle receiver over the wireless link, so the requirement of asking the communication unit to make specific measurements, collect the results, and communicate them back is easily met. After despreading and some additional signal processing, an AGPS receiver returns back "pseudoranges"—that is, ranges measured without taking into account the discrepancy between satellite and receiver clocks—to the AGPS server, which then calculates the vehicle's location. The vehicle can even complete the location fix itself without returning any data to the server.

Sensitivity assistance, also known as modulation wipe-off, provides another enhancement to detection of GPS signals in the vehicle's receiver. The sensitivity-assistance message contains predicted data bits of the GPS navigation message, which are expected to modulate the GPS signal of specific satellites at specified times. The mobile station receiver can therefore remove bit modulation in the received GPS signal prior to coherent integration. By extending coherent integration beyond the 20-ms GPS data-bit period—to a second or more when the receiver is stationary and to 400 ms when it is fast-moving—this approach improves receiver sensitivity. Sensitivity assistance provides an additional 3-to-4-dB improvement in receiver sensitivity. Because some of the gain provided by the basic assistance—

code phases and Doppler shift values—is lost when integrating the GPS receiver chain into a mobile system, this can prove crucial to making a practical receiver.

Achieving optimal performance of sensitivity assistance in TIA/EIA-95 CDMA systems is relatively straightforward because base stations and mobiles synchronize with GPS time. Given that global system for mobile communication (GSM), time division multiple access (TDMA), or advanced mobile phone service (AMPS) systems do not maintain such stringent synchronization, implementation of sensitivity assistance and AGPS technology in general will require novel approaches to satisfy the timing requirement. The standardized solution for GSM and TDMA adds time calibration receivers in the field—location measurement units—that can monitor both the wireless-system timing and GPS signals used as a timing reference.

Many factors affect the accuracy of geolocation technologies, especially terrain variations such as hilly versus flat and environmental differences such as urban versus suburban versus rural. Other factors, like cell size and interference, have smaller but noticeable effects. Hybrid approaches that use multiple geolocation technologies appear to be the most robust solution to problems of accuracy and coverage.

AGPS provides a natural fit for hybrid solutions because it uses the wireless network to supply assistance data to GPS receivers in vehicles. This feature makes it easy to augment the assistance-data message with low-accuracy distances from receiver to base stations measured by the network equipment. Such hybrid solutions benefit from the high density of base stations in dense urban environments, which are hostile to GPS signals. Conversely, rural environments—where base stations are too scarce for network-based solutions to achieve high accuracy—provide ideal operating conditions for AGPS because GPS works well there.

SAW transponders can also be placed in the license plates **287** (FIG. **26**) of all vehicles at nominal cost. An appropriately equipped automobile can then determine the angular location of vehicles in its vicinity. If a third antenna **286** is placed at the center of the vehicle front, then an indication of the distance to a license plate of a preceding vehicle can also be obtained as described above. Thus, once again, a single interrogator coupled with multiple antenna systems can be used for many functions. Alternately, if more than one SAW transponders is placed spaced apart on a vehicle and if two antennas are on the other vehicle, then the direction and position of the SAW vehicle can be determined by the receiving vehicle.

A general SAW temperature and pressure gage which can be wireless and powerless is shown generally at **300** located in the sidewall **310** of a fluid container **320** in FIG. **27**. A pressure sensor **301** is located on the inside of the container **320**, where it measures deflection of the container wall, and the fluid temperature sensor **302** on the outside. The temperature measuring SAW **300** can be covered with an insulating material to avoid influence from the ambient temperature outside of the container **320**.

A SAW load sensor can also be used to measure load in the vehicle suspension system powerless and wirelessly as shown in FIG. **28**. FIG. **28A** illustrates a strut **315** such as either of the rear struts of the vehicle of FIG. **28**. A coil spring **320** stresses in torsion as the vehicle encounters disturbances from the road and this torsion can be measured using SAW strain gages as described in U.S. Pat. No. 5,585,571 for measuring the torque in shafts. This concept is also disclosed in U.S. Pat. No. 5,714,695. The disclosures of both patents are incorporated herein by reference. The use of

SAW strain gages to measure the torsional stresses in a spring, as shown in FIG. **28**B, and in particular in an automobile suspension spring has, to the knowledge of the inventors, not been heretofore disclosed. In FIG. **28**B, the strain measured by SAW strain gage **322** is subtracted from the strain measured by SAW strain gage **321** to get the temperature compensated strain in spring **320**.

Since a portion of the dynamic load is also carried by the shock absorber, the SAW strain gages **321** and **322** will only measure the steady or average load on the vehicle. However, additional SAW strain gages **325** can be placed on a piston rod **326** of the shock absorber to obtain the dynamic load. These load measurements can then be used for active or passive vehicle damping or other stability control purposes.

FIG. **29** illustrates a vehicle passenger compartment, and the engine compartment, with multiple SAW temperature sensors **330**. SAW temperature sensors are distributed throughout the passenger compartment, such as on the A-pillar, on the B-pillar, on the steering wheel, on the seat, on the ceiling, on the headliner, and on the rear glass and generally in the engine compartment. These sensors, which can be independently coded with different IDs and different delays, can provide an accurate measurement of the temperature distribution within the vehicle interior. Such a system can be used to tailor the heating and air conditioning system based on the temperature at a particular location in the passenger compartment. If this system is augmented with occupant sensors, then the temperature can be controlled based on seat occupancy and the temperature at that location. If the occupant sensor system is based on ultrasonics than the temperature measurement system can be used to correct the ultrasonic occupant sensor system for the speed of sound within the passenger compartment. Without such a correction, the error in the sensing system can be as large as about 20 percent.

In one case, the SAW temperature sensor can be made from PVDF film and incorporated within the ultrasonic transducer assembly. For the 40 kHz ultrasonic transducer case, for example, the SAW temperature sensor would return the several pulses sent to drive the ultrasonic transducer to the control circuitry using the same wires used to transmit the pulses to the transducer after a delay that is proportional to the temperature within the transducer housing. Thus a very economical device can add this temperature sensing function using much of the same hardware that is already present for the occupant sensing system. Since the frequency is low, PVDF could be fabricated into a very low cost temperature sensor for this purpose. Other piezoelectric materials could also be used.

Other sensors can be combined with the temperature sensors **330**, or used separately, to measure carbon dioxide, carbon monoxide, alcohol, humidity or other desired chemicals as discussed above.

The SAW temperature sensors **330** provide the temperature at their mounting location to a processor unit **332** via an interrogator with the processor unit including appropriate control algorithms for controlling the heating and air conditioning system based on the detected temperatures. The processor unit can control, e.g., which vents in the vehicle are open and closed, the flow rate through vents and the temperature of air passing through the vents. In general, the processor unit can control whatever adjustable components are present or form part of the heating and air conditioning system.

As shown in FIG. **29**, a child seat **334** is present on the rear vehicle seat. The child seat **334** can be fabricated with one or more RFID tags or SAW tags **336**. The RFID tag(s) and SAW tag(s) can be constructed to provide information on the occupancy of the child seat, i.e., whether a child is present, based on the weight. Also, the mere transmission of waves from the RFID tag(s) or SAW tag(s) on the child seat would be indicative of the presence of a child seat. The RFID tag(s) and SAW tag(s) can also be constructed to provide information about the orientation of the child seat, i.e., whether it is facing rearward or forward. Such information about the presence and occupancy of the child seat and its orientation can be used in the control of vehicular systems, such as the vehicle airbag system. In this case, a processor would control the airbag system and would receive information from the RFID tag(s) and SAW tag(s) via an interrogator.

There are many applications for which knowledge of the pitch and/or roll orientation of a vehicle or other object is desired. An accurate tilt sensor can be constructed using SAW devices. Such a sensor is illustrated in FIG. **30**A and designated **350**. This sensor **350** utilizes a substantially planar and rectangular mass **351** and four supporting SAW devices **352** which are sensitive to gravity. For example, the mass act to deflect a membrane on which the SAW device resides thereby straining the SAW device. Other properties can also be used for a tilt sensor such as the direction of the earth's magnetic field. SAW devices **352** are shown arranged at the corners of the planar mass **351**, but it must be understood that this arrangement is a preferred embodiment only and not intended to limit the invention. A fifth SAW device **353** can be provided to measure temperature. By comparing the outputs of the four SAW devices **352**, the pitch and roll of the automobile can be measured. This sensor **350** can be used to correct errors in the SAW rate gyros described above. If the vehicle has been stationary for a period of time, the yaw SAW rate gyro can initialized to 0 and the pitch and roll SAW gyros initialized to a value determined by the tilt sensor of FIG. **30**A. Many other geometries of tilt sensors utilizing one or more SAW devices can now be envisioned for automotive and other applications. In particular, an alternate preferred configuration is illustrated in FIG. **30**B where a triangular geometry is used. In this embodiment, the planar mass is triangular and the SAW devices **352** are arranged at the corners, although as with FIG. **30**A, this is a non-limiting, preferred embodiment.

Either of the SAW accelerometers described above can be utilized for crash sensors as shown in FIG. **31**. These accelerometers have a substantially higher dynamic range than competing accelerometers now used for crash sensors such as those based on MEMS silicon springs and masses and others based on MEMS capacitive sensing. As discussed above, this is partially a result of the use of frequency or phase shifts which can be easily measured over a very wide range. Additionally, many conventional accelerometers that are designed for low acceleration ranges are unable to withstand high acceleration shocks without breaking. This places practical limitations on many accelerometer designs so that the stresses in the silicon springs are not excessive. Also for capacitive accelerometers, there is a narrow limit over which distance, and thus acceleration, can be measured.

The SAW accelerometer for this particular crash sensor design is housed in a container **361** which is assembled into a housing **362** and covered with a cover **363**. This particular implementation shows a connector **364** indicating that this sensor would require power and the response would be provided through wires. Alternately, as discussed for other devices above, the connector **364** can be eliminated and the information and power to operate the device transmitted wirelessly. Such sensors can be used as frontal, side or rear

impact sensors. They can be used in the crush zone, in the passenger compartment or any other appropriate vehicle location. If two such sensors are separated and have appropriate sensitive axes, then the angular acceleration of the vehicle can be also be determined. Thus, for example, forward-facing accelerometers mounted in the vehicle side doors can used to measure the yaw acceleration of the vehicle. Alternately two vertical sensitive axis accelerometers in the side doors can be used to measure the roll acceleration of vehicle, which would be useful for rollover sensing.

Although piezoelectric SAW devices normally use rigid material such as quartz or lithium niobate, it is also possible to utilize polyvinylidene fluoride (PVDF) providing the frequency is low. A piece of PVDF film can also be used as a sensor of tire flexure by itself. Such a sensor is illustrated in FIGS. **32**A and **32**B at **400**. The output of flexure of the PVDF film can be used to supply power to a silicon microcircuit that contains pressure and temperature sensors. The waveform of the output from the PVDF film also provides information as to the flexure of an automobile tire and can be used to diagnose problems with the tire as well as the tire footprint in a manner similar to the device described in FIG. **15**. In this case, however, the PVDF film supplies sufficient power to permit significantly more transmission energy to be provided. The frequency and informational content can be made compatible with the SAW interrogator described above such that the same interrogator can be used. The power available for the interrogator, however, can be significantly greater thus increasing the reliability and reading range of the system.

There is a general problem with tire pressure monitors as well as systems that attempt to interrogate passive SAW or electronic RFID type devices in that the FCC severely limits the frequencies and radiating power that can be used. Once it becomes evident that these systems will eventually save many lives, the FCC can be expected to modify their position. In the meantime, various schemes can be used to help alleviate this problem. The lower frequencies that have been opened for automotive radar permit higher power to be used and they could be candidates for the devices discussed above. It is also possible, in some cases, to transmit power on multiple frequencies and combine the received power to boost the available energy. Energy can of course be stored and periodically used to drive circuits and work is ongoing to reduce the voltage required to operate semiconductors. The devices of this invention will make use of some or all of these developments as they take place.

If the vehicle has been at rest for a significant time period, power will leak from the storage capacitors and will not be available for transmission. However, a few tire rotations are sufficient to provide the necessary energy.

U.S. patent application Ser. No. 08/819,609, assigned to the current assignee of this invention, provides multiple means for determining the amount of gas in a gas tank. Using the SAW pressure devices of this invention, multiple pressure sensors can be placed at appropriate locations within a fuel tank to measure the fluid pressure and thereby determine the quantity of fuel remaining in the tank. This is illustrated in FIG. **33**. In this example, four SAW pressure transducers **402** are placed on the bottom of the fuel tank and one SAW pressure transducer **403** is placed at the top of the fuel tank to eliminate the effects of vapor pressure within tank. Using neural networks, or other pattern recognition techniques, the quantity of fuel in the tank can be accurately determined from these pressure readings in a manner similar that described the '609 patent application. The SAW measuring device illustrated in FIG. **33**A combines temperature and pressure measurements in a single unit using parallel paths **405** and **406** in the same manner as described above.

Occupant weight sensors can give erroneous results if the seatbelt is pulled tight pushing the occupant into the seat. This is particularly a problem when the seatbelt is not attached to the seat. For such cases, it has been proposed to measure the tension in various parts of the seatbelt. Using conventional technology requires that such devices be hardwired into the vehicle complicating the wire harness.

With reference to FIG. **34**, using a SAW strain gage as described above, the tension in the seat belt **500** can be measured without the requirement of power or signal wires. FIG. **34** illustrates a powerless and wireless passive SAW strain gage based device **502** for this purpose. There are many other places that such a device can be mounted to measure the tension in the seatbelt at one or at multiple places.

FIG. **35** illustrates another version of a tire temperature and/or pressure monitor **510**. Monitor **510** may include at an inward end, any one of the temperature transducers or sensors described above and/or any one of the pressure transducers or sensors described above, or any one of the combination temperature and pressure transducers or sensors described above.

The monitor **510** has an elongate body attached through the wheel rim **513** typically on the inside of the tire so that the under-vehicle mounted antenna(s) have a line of sight view of antenna **515**. Monitor **510** is connected to an inductive wire **512**, which matches the output of the device with the antenna **515**, which is part of the device assembly. Insulating material **511** surrounds the body which provides an air tight seal and prevents electrical contact with the wheel rim **513**.

FIG. **36**A shows a schematic of a prior art airbag module deployment scheme in which sensors, which detect data for use in determining whether to deploy an airbag in the airbag module, are wired to an electronic control unit (ECU) and a command to initiate deployment of the airbag in the airbag module is sent wirelessly.

By contrast, as shown in FIG. **36**B, in accordance with the invention, the sensors are wireless connected to the electronic control unit and thus transmit data wirelessly. The ECU is however wired to the airbag module.

SAW sensors also have applicability to various other sectors of the vehicle, including the powertrain, chassis, and occupant comfort and convenience. For example, SAW sensors have applicability to sensors for the powertrain area including oxygen sensors, gear-tooth Hall effect sensors, variable reluctance sensors, digital speed and position sensors, oil condition sensors, rotary position sensors, low pressure sensors, manifold absolute pressure/manifold air temperature (MAP/MAT) sensors, medium pressure sensors, turbo pressure sensors, knock sensors, coolant/fluid temperature sensors, and transmission temperature sensors.

SAW sensors for chassis applications include gear-tooth Hall effect sensors, variable reluctance sensors, digital speed and position sensors, rotary position sensors, non-contact steering position sensors, and digital ABS (anti-lock braking system) sensors.

SAW sensors for the occupant comfort and convenience area include low-pressure sensors, HVAC temperature and humidity sensors, air temperature sensors, and oil condition sensors.

SAW sensors also have applicability such areas as controlling evaporative emissions, transmission shifting, mass air flow meters, oxygen, NOx and hydrocarbon sensors.

SAW based sensors are particularly useful in high temperature environments where many other technologies fail.

SAW sensors can facilitate compliance with U.S. regulations concerning evaporative system monitoring in vehicles, through a SAW fuel vapor pressure and temperature sensors that measure fuel vapor pressure within the fuel tank as well as temperature. If vapors leak into the atmosphere, the pressure within the tank drops. The sensor notifies the system of a fuel vapor leak, resulting in a warning signal to the driver and/or notification to a repair facility. This application is particularly important since the condition within the furl tank can be ascertained wirelessly reducing the chance of a fuel fire in an accident. The same interrogator that monitors the tire pressure SAW sensors can also monitor the fuel vapor pressure and temperature sensors resulting in significant economies.

A SAW humidity sensor can be used for measuring the relative humidity and the resulting information can be input to the engine management system or the heating, ventilation, and air conditioning (HVAC) system for more efficient operation. The relative humidity of the air entering an automotive engine impacts the engine's combustion efficiency; i.e., the ability of the spark plugs to ignite the fuel/air mixture in the combustion chamber at the proper time. A SAW humidity sensor in this case can measure the humidity level of the incoming engine air, helping to calculate a more precise fuel/air ratio for improved fuel economy and reduced emissions.

Dew point conditions are reached when the air is fully saturated with water. When the cabin dew point temperature matches the windshield glass temperature, water from the air condenses quickly, creating frost or fog. A SAW humidity sensor with a temperature-sensing element and a window glass-temperature-sensing element can prevent the formation of visible fog formation by automatically controlling the HVAC system.

Among the inventions disclosed above is an arrangement for obtaining and conveying information about occupancy of a passenger compartment of a vehicle comprises at least one wave-receiving sensor for receiving waves from the passenger compartment, generating means coupled to the wave-receiving sensor(s) for generating information about the occupancy of the passenger compartment based on the waves received by the wave-receiving sensor(s) and communications means coupled to the generating means for transmitting the information about the occupancy of the passenger compartment. As such, response personnel can receive the information about the occupancy of the passenger compartment and respond appropriately, if necessary. There may be several wave-receiving sensors and they may be, e.g., ultrasonic wave-receiving sensors, electromagnetic wave-receiving sensors, capacitance or electric field sensors, or combinations thereof. The information about the occupancy of the passenger compartment can include the number of occupants in the passenger compartment, as well as whether each occupant is moving non-reflexively and breathing. A transmitter may be provided for transmitting waves into the passenger compartment such that each wave-receiving sensor receives waves transmitted from the transmitter and modified by passing into and at least partially through the passenger compartment. One or more memory units may be coupled to the generating means for storing the information about the occupancy of the passenger compartment and to the communications means. The communications means then can interrogate the memory unit(s) upon a crash of the vehicle to thereby obtain the information about the occupancy of the passenger compartment. In one particularly useful embodiment, means for determining the health state of at least one occupant are provided, e.g., a heartbeat sensor, a motion sensor such as a micropower impulse radar sensor for detecting motion of the at least one occupant and motion sensor for determining whether the occupant(s) is/are breathing, and coupled to the communications means. The communications means can interrogate the health state determining means upon a crash of the vehicle to thereby obtain and transmit the health state of the occupant(s). The health state determining means can also comprise a chemical sensor for analyzing the amount of carbon dioxide in the passenger compartment or around the at least one occupant or for detecting the presence of blood in the passenger compartment. Movement of the occupant can be determined by monitoring the weight distribution of the occupant(s), or an analysis of waves from the space occupied by the occupant(s). Each wave-receiving sensor generates a signal representative of the waves received thereby and the generating means may comprise a processor for receiving and analyzing the signal from the wave-receiving sensor in order to generate the information about the occupancy of the passenger compartment. The processor can comprise pattern recognition means for classifying an occupant of the seat so that the information about the occupancy of the passenger compartment includes the classification of the occupant. The wave-receiving sensor may be a micropower impulse radar sensor adapted to detect motion of an occupant whereby the motion of the occupant or absence of motion of the occupant is indicative of whether the occupant is breathing. As such, the information about the occupancy of the passenger compartment generated by the generating means is an indication of whether the occupant is breathing. Also, the wave-receiving sensor may generate a signal representative of the waves received thereby and the generating means receive this signal over time and determine whether any occupants in the passenger compartment are moving. As such, the information about the occupancy of the passenger compartment generated by the generating means includes the number of moving and non-moving occupants in the passenger compartment.

A related method for obtaining and conveying information about occupancy of a passenger compartment of a vehicle comprises the steps of receiving waves from the passenger compartment, generating information about the occupancy of the passenger compartment based on the received waves, and transmitting the information about the occupancy of the passenger compartment whereby response personnel can receive the information about the occupancy of the passenger compartment. Waves may be transmitted into the passenger compartment whereby the transmitted waves are modified by passing into and at least partially through the passenger compartment and then received. The information about the occupancy of the passenger compartment may be stored in at least one memory unit which is subsequently interrogated upon a crash of the vehicle to thereby obtain the information about the occupancy of the passenger compartment. A signal representative of the received waves can be generated by sensors and analyzed in order to generate the information about the state of health of at least one occupant of the passenger compartment and/or to generate the information about the occupancy of the passenger compartment (i.e., determine non-reflexive movement and/or breathing indicating life). Pattern recognition techniques, e.g., a trained neural network, can be applied to analyze the signal and thereby recognize and identify any occupants of the passenger compartment. In this case, the identification of the occupants of the passenger compartment

can be included into the information about the occupancy of the passenger compartment.

All of the above-described methods and apparatus, as well as those further described below, may be used in conjunction with one another and in combination with the methods and apparatus for optimizing the driving conditions for the occupants of the vehicle described herein.

Also described above is an embodiment of a component diagnostic system for diagnosing the component in accordance with the invention which comprises a plurality of sensors not directly associated with the component, i.e., independent therefrom, such that the component does not directly affect the sensors, each sensor detecting a signal containing information as to whether the component is operating normally or abnormally and outputting a corresponding electrical signal, processor means coupled to the sensors for receiving and processing the electrical signals and for determining if the component is operating abnormally based on the electrical signals, and output means coupled to the processor means for affecting another system within the vehicle if the component is operating abnormally. The processor means preferably comprise pattern recognition means such as a trained pattern recognition algorithm, a neural network, modular neural networks, an ensemble of neural networks, a cellular neural network, or a support vector machine. In some cases, fuzzy logic will be used which can be combined with a neural network to form a neural fuzzy algorithm. The another system may be a display for indicating the abnormal state of operation of the component arranged in a position in the vehicle to enable a driver of the vehicle to view the display and thus the indicated abnormal operation of the component. At least one source of additional information, e.g., the time and date, may be provided and input means coupled to the vehicle for inputting the additional information into the processor means. The another system may also be a warning device including transmission means for transmitting information related to the component abnormal operating state to a site remote from the vehicle, e.g., a vehicle repair facility.

In another embodiment of the component diagnostic system discussed above, at least one sensor detects a signal containing information as to whether the component is operating normally or abnormally and outputs a corresponding electrical signal. A processor or other computing device is coupled to the sensor(s) for receiving and processing the electrical signal(s) and for determining if the component is operating abnormally based thereon. The processor preferably comprises or embodies a pattern recognition algorithm for analyzing a pattern within the signal detected by each sensor. An output device (or multiple output devices) is coupled to the processor for affecting another system within the vehicle if the component is operating abnormally. The other system may be a display as mentioned above or a warning device.

A method for automatically monitoring one or more components of a vehicle during operation of the vehicle on a roadway entails, as discussed above, the steps of monitoring operation of the component in order to detect abnormal operation of the component, e.g., in one or the ways described above, and if abnormal operation of the component is detected, automatically directing the vehicle off of the restricted roadway. For example, in order to automatically direct the vehicle off of the restricted roadway, a signal representative of the abnormal operation of the component may be generated and directed to a guidance system of the vehicle that guides the movement of the vehicle. Possibly the directing the vehicle off of the restricted roadway may entail applying satellite positioning techniques or ground-based positioning techniques to enable the current position of the vehicle to be determined and a location off of the restricted highway to be determined and thus a path for the movement of the vehicle. Re-entry of the vehicle onto the restricted roadway may be prevented until the abnormal operation of the component is satisfactorily addressed.

Although several preferred embodiments are illustrated and described above, there are possible combinations using other signals and sensors for the components and different forms of the neural network implementation or different pattern recognition technologies that perform the same functions which can be utilized in accordance with the invention. Also, although the neural network and modular neural networks have been described as an example of one means of pattern recognition, other pattern recognition means exist and still others are being developed which can be used to identify potential component failures by comparing the operation of a component over time with patterns characteristic of normal and abnormal component operation. In addition, with the pattern recognition system described above, the input data to the system may be data which has been pre-processed rather than the raw signal data either through a process called "feature extraction" or by various mathematical transformations. Also, any of the apparatus and methods disclosed herein may be used for diagnosing the state of operation or a plurality of discrete components.

In other embodiments disclosed above, the state of the entire vehicle is diagnosed whereby two or more sensors, preferably acceleration sensors and gyroscopes, detect the state of the vehicle and if the state is abnormal, output means are coupled to the processor means for affecting another system in the vehicle. The another system may be the steering control system, the brake system, the accelerator or the frontal or side occupant protection system. An exemplifying control system for controlling a part of the vehicle in accordance with the invention thus comprises a plurality of sensor systems mounted at different locations on the vehicle, each sensor system providing a measurement related to a state of the sensor system or a measurement related to a state of the mounting location, and a processor coupled to the sensor systems and arranged to diagnose the state of the vehicle based on the measurements of the sensor system, e.g., by the application of a pattern recognition technique. The processor controls the part based at least in part on the diagnosed state of the vehicle. At least one of the sensor systems may be a high dynamic range accelerometer or a sensor selected from a group consisting of a single axis acceleration sensor, a double axis acceleration sensor, a triaxial acceleration sensor and a gyroscope, and may optionally include an RFID response unit. The gyroscope may be a MEMS-IDT gyroscope including a surface acoustic wave resonator which applies standing waves on a piezoelectric substrate. If an RFID response unit is present, the control system would then comprise an RFID interrogator device which causes the RFID response unit(s) to transmit a signal representative of the measurement of the sensor system associated therewith to the processor.

The state of the vehicle diagnosed by the processor may be the vehicle's angular motion, angular acceleration and/or angular velocity. As such, the steering system, braking system or throttle system may be controlled by the processor in order to maintain the stability of the vehicle. The processor can also be arranged to control an occupant restraint or protection device in an attempt to minimize injury to an occupant.

The state of the vehicle diagnosed by the processor may also be a determination of a location of an impact between

the vehicle and another object. In this case, the processor can forecast the severity of the impact using the force/crush properties of the vehicle at the impact location and control an occupant restraint or protection device based at least in part on the severity of the impact.

The system can also include a weight sensing system coupled to a seat in the vehicle for sensing the weight of an occupying item of the seat. The weight sensing system is coupled to the processor whereby the processor controls deployment or actuation of the occupant restraint or protection device based on the state of the vehicle and the weight of the occupying item of the seat sensed by the weight sensing system.

A display may be coupled to the processor for displaying an indication of the state of the vehicle as diagnosed by the processor. A warning device may be coupled to the processor for relaying a warning to an occupant of the vehicle relating to the state of the vehicle as diagnosed by the processor. Further, a transmission device may be coupled to the processor for transmitting a signal to a remote site relating to the state of the vehicle as diagnosed by the processor.

The state of the vehicle diagnosed by the processor may include angular acceleration of the vehicle whereby angular velocity and angular position or orientation are derivable from the angular acceleration. The processor can then be arranged to control the vehicle's navigation system based on the angular acceleration of the vehicle.

A method for controlling a part of the vehicle in accordance with the invention comprises the step of mounting a plurality of sensor systems at different locations on the vehicle, measuring a state of the sensor system or a state of the respective mounting location of the sensor system, diagnosing the state of the vehicle based on the measurements of the state of the sensor systems or the state of the mounting locations of the sensor systems, and controlling the part based at least in part on the diagnosed state of the vehicle. The state of the sensor system may be any one or more of the acceleration, angular acceleration, angular velocity or angular orientation of the sensor system. Diagnosis of the state of the vehicle may entail determining whether the vehicle is stable or is about to rollover or skid and/or determining a location of an impact between the vehicle and another object. Diagnosis of the state of the vehicle may also entail determining angular acceleration of the vehicle based on the acceleration measured by accelerometers if multiple accelerometers are present as the sensor systems.

Another control system for controlling a part of the vehicle in accordance with the invention comprises a plurality of sensor systems mounted on the vehicle, each providing a measurement of a state of the sensor system or a state of the mounting location of the sensor system and generating a signal representative of the measurement, and a pattern recognition system for receiving the signals from the sensor systems and diagnosing the state of the vehicle based on the measurements of the sensor systems. The pattern recognition system generates a control signal for controlling the part based at least in part on the diagnosed state of the vehicle. The pattern recognition system may comprise one or more neural networks. The features of the control system described above may also be incorporated into this control system to the extent feasible.

The state of the vehicle diagnosed by the pattern recognition system may include a state of an abnormally operating component whereby the pattern recognition system is designed to identify a potentially malfunctioning component based on the state of the component measured by the sensor systems and determine whether the identified component is operating abnormally based on the state of the component measured by the sensor systems.

In one preferred embodiment, the pattern recognition system may comprise a neural network system and the state of the vehicle diagnosed by the neural network system includes a state of an abnormally operating component. The neural network system includes a first neural network for identifying a potentially malfunctioning component based on the state of the component measured by the sensor systems and a second neural network for determining whether the identified component is operating abnormally based on the state of the component measured by the sensor systems.

Modular neural networks can also be used whereby the neural network system includes a first neural network arranged to identify a potentially malfunctioning component based on the state of the component measured by the sensor systems and a plurality of additional neural networks. Each of the additional neural networks is trained to determine whether a specific component is operating abnormally so that the measurements of the state of the component from the sensor systems are input into that one of the additional neural networks trained on a component which is substantially identical to the identified component.

Another method for controlling a part of the vehicle comprises the steps of mounting a plurality of sensor systems on the vehicle, measuring a state of the sensor system or a state of the respective mounting location of the sensor system, generating signals representative of the measurements of the sensor systems, inputting the signals into a pattern recognition system to obtain a diagnosis of the state of the vehicle and controlling the part based at least in part on the diagnosis of the state of the vehicle.

In one notable embodiment, a potentially malfunctioning component is identified by the pattern recognition system based on the states measured by the sensor systems and the pattern recognition system determine whether the identified component is operating abnormally based on the states measured by the sensor systems. If the pattern recognition system comprises a neural network system, identification of the component entails inputting the states measured by the sensor systems into a first neural network of the neural network system and the determination of whether the identified component is operating abnormally entails inputting the states measured by the sensor systems into a second neural network of the neural network system. A modular neural network system can also be applied in which the states measured by the sensor systems are input into a first neural network and a plurality of additional neural networks are provided, each being trained to determine whether a specific component is operating abnormally, whereby the states measured by the sensor systems are input into that one of the additional neural networks trained on a component which is substantially identical to the identified component.

Another control system for controlling a part of the vehicle based on occupancy of the seat in accordance with the invention comprises a plurality of strain gages mounted in connection with the seat, each measuring strain of a respective mounting location caused by occupancy of the seat, and a processor coupled to the strain gages and arranged to determine the weight of an occupying item based on the strain measurements from the strain gages over a period of time, i.e., dynamic measurements. The processor controls the part based at least in part on the determined weight of the occupying item of the seat. The processor can also determine motion of the occupying item of the seat

based on the strain measurements from the strain gages over the period of time. One or more accelerometers may be mounted on the vehicle for measuring acceleration in which case, the processor may control the part based at least in part on the determined weight of the occupying item of the seat and the acceleration measured by the accelerometer(s).

By comparing the output of various sensors in the vehicle, it is possible to determine activities that are affecting parts of the vehicle while not affecting other parts. For example, by monitoring the vertical accelerations of various parts of the vehicle and comparing these accelerations with the output of strain gage load cells placed on the seat support structure, a characterization can be made of the occupancy of the seat. Not only can the weight of an object occupying the seat be determined, but also the gross motion of such an object can be ascertained and thereby an assessment can be made as to whether the object is a life form such as a human being. Strain gage weight sensors are disclosed in U.S. patent application Ser. No. 09/193,209 filed Nov. 17, 1998 (corresponding to International Publication No. WO 00/29257), which is incorporated herein by reference its entirety as if the entire application were set forth herein. In particular, the inventors contemplate the combination of all of the ideas expressed in this patent application with those expressed in the current invention.

Also disclosed above is a vehicle including a diagnostic system arranged to diagnose the state of the vehicle or the state of a component of the vehicle and generate an output indicative or representative thereof and a communications device coupled to the diagnostic system and arranged to transmit the output of the diagnostic system. The diagnostic system may comprise a plurality of vehicle sensors mounted on the vehicle, each sensor providing a measurement related to a state of the sensor or a measurement related to a state of the mounting location, and a processor coupled to the sensors and arranged to receive data from the sensors and process the data to generate the output indicative or representative of the state of the vehicle or the state of a component of the vehicle. The sensors may be wirelessly coupled to the processor and arranged at different locations on the vehicle. The processor may embody a pattern recognition algorithm trained to generate the output from the data received from the sensors, such as a neural network, fuzzy logic, sensor fusion and the like, and be arranged to control one or more parts of the vehicle based on the output indicative or representative of the state of the vehicle or the state of a component of the vehicle. The state of the vehicle can include angular motion of the vehicle. A display may be arranged in the vehicle in a position to be visible from the passenger compartment. Such as display is coupled to the diagnostic system and arranged to display the diagnosis of the state of the vehicle or the state of a component of the vehicle. A warning device may also be coupled to the diagnostic system for relaying a warning to an occupant of the vehicle relating to the state of the vehicle or the state of the component of the vehicle as diagnosed by the diagnostic system. The communications device may comprise a cellular telephone system including an antenna as well as other similar or different electronic equipment capable of transmitting a signal to a remote location, optionally via a satellite. Transmission via the Internet, i.e., to a web site or host computer associated with the remote location is also a possibility for the invention. If the vehicle is considered it sown site, then the transmission would be a site-to-site transmission via the Internet.

An occupant sensing system can be provided to determine at least one property or characteristic of occupancy of the vehicle. In this case, the communications device is coupled to. the occupant sensing system and transmits the determined property or characteristic of occupancy of the vehicle. In a similar manner, at least one environment sensor can be provided, each sensing a state of the environment around the vehicle. In this case, the communications device is coupled to the environment sensor(s) and transmits the sensed state of the environment around the vehicle. Moreover, a location determining system, optionally incorporating GPS technology, could be provided on the vehicle to determine the location of the vehicle and transmitted to the remote location along with the diagnosis of the state of the vehicle or its component. A memory unit may be coupled to the diagnostic system and the communications device. The memory unit receives the diagnosis of the state of the vehicle or the state of a component of the vehicle from the diagnostic system and stores the diagnosis. The communications device then interrogates the memory unit to obtain the stored diagnosis to enable transmission thereof, e.g., at periodic intervals.

The sensors may be any known type of sensor including, but not limited to, a single axis acceleration sensor, a double axis acceleration sensor, a triaxial acceleration sensor and a gyroscope. The sensors may include an RFID response unit and an RFID interrogator device which causes the RFID response units to transmit a signal representative of the measurement of the associated sensor to the processor. In addition to or instead or an RFID-based system, one or more SAW sensors can be arranged on the vehicle, each receiving a signal and returning a signal modified by virtue of the state of the sensor or the state of the mounting location of the sensor. For example, the SAW sensor can measure temperature and/or pressure of a component of the vehicle or in a certain location or space on the vehicle, or the concentration and/or presence of a chemical.

A method for monitoring a vehicle comprises diagnosing the state of the vehicle or the state of a component of the vehicle by means of a diagnostic system arranged on the vehicle, generating an output indicative or representative of the diagnosed state of the vehicle or the diagnosed state of the component of the vehicle, and transmitting the output to a remote location. Transmission of the output to a remote location may entail arranging a communications device comprising a cellular telephone system including an antenna on the vehicle. The output may be to a satellite for transmission from the satellite to the remote location. The output could also be transmitted via the Internet to a web site or host computer associated with the remote location.

It is important to note that raw sensor data is not transmitted from the vehicle the remote location for analysis and processing by the devices and/or personnel at the remote location. Rather, in accordance with the invention, a diagnosis of the vehicle or the vehicle component is performed on the vehicle itself and this resultant diagnosis is transmitted. The diagnosis of the state of the vehicle may encompass determining whether the vehicle is stable or is about to rollover or skid and/or determining a location of an impact between the vehicle and another object. A display may be arranged in the vehicle in a position to be visible from the passenger compartment in which case, the state of the vehicle or the state of a component of the vehicle is displayed thereon. Further, a warning can be relayed to an

occupant of the vehicle relating to the state of the vehicle. In addition to the transmission of vehicle diagnostic information obtained by analysis of data from sensors performed on the vehicle, at least one property or characteristic of occupancy of the vehicle may be determined (such as the number of occupants, the status of the occupants-breathing or not, injured or not, etc.) and transmitted to a remote location, the same or a different remote location to which the diagnostic information is sent. The information can also be sent in a different manner than the information relating to the diagnosis of the vehicle.

Additional information for transmission by the components on the vehicle may include a state of the environment around the vehicle, for example, the temperature, pressure, humidity, etc. in the vicinity of the vehicle, and the location of the vehicle. A memory unit may be provided in the vehicle, possibly as part of a microprocessor, and arranged to receive the diagnosis of the state of the vehicle or the state of the component of the vehicle and store the diagnosis. As such, this memory unit can be periodically interrogated to obtain the stored diagnosis to enable transmission thereof.

Diagnosis of the state of the vehicle or the state of the component of the vehicle may entail mounting a plurality of sensors on the vehicle, measuring a state of each sensor or a state of the mounting location of each sensor and diagnosing the state of the vehicle or the state of a component of the vehicle based on the measurements of the state of the sensors or the state of the mounting locations of the sensors. These functions can be achieved by a processor which is wirelessly coupled to the sensors. The sensors can optionally be provided with RFID technology, i.e., an RFID response unit, whereby an RFID interrogator device is mounted on the vehicle and signals transmitted via the RFID interrogator device causes the RFID response units of any properly equipped sensors to transmit a signal representative of the measurements of that sensor to the processor. SAW sensors can also be used, in addition to or instead of RFID-based sensors.

One embodiment of the diagnostic module in accordance with the invention utilizes information which already exists in signals emanating from various vehicle components along with sensors which sense these signals and, using pattern recognition techniques, compares these signals with patterns characteristic of normal and abnormal component performance to predict component failure, vehicle instability or a crash earlier than would otherwise occur if the diagnostic module was not utilized. If fully implemented, this invention is a total diagnostic system of the vehicle. In most implementations, the module is attached to the vehicle and electrically connected to the vehicle data bus where it analyzes data appearing on the bus to diagnose components of the vehicle. In some implementations, multiple distributed accelerometers and/or microphones are present on the vehicle and, in some cases, some of the sensors will communicate using wireless technology to the vehicle bus or directly to the diagnostic module.

Although several preferred embodiments are illustrated and described above, there are possible combinations using other geometries, sensors, materials and different dimensions for the components that perform the same functions. This invention is not limited to the above embodiments and should be determined by the following claims.

I claim:

1. In a motor vehicle, a control system for controlling an occupant restraint system, comprising:

a plurality of electronic sensors mounted at different locations on the vehicle, each of said sensors providing a measurement related to a state of said sensor or a measurement related to a state of the mounting location; and

a processor coupled to said sensors and arranged to diagnose the state of the vehicle based on the measurements of said sensors,

said processor being arranged to control the occupant restraint system based at least in part on the diagnosed state of the vehicle in an attempt to minimize injury to an occupant.

2. The vehicle of claim **1**, wherein at least one of said sensors is selected from a group consisting of a single axis acceleration sensor, a double axis acceleration sensor, a triaxial acceleration sensor and a gyroscope.

3. The vehicle of claim **1**, wherein at least one of said sensors includes an RF (radio frequency) response unit, further comprising at least one RF interrogator device, said at least one interrogator device causing said RF response unit of said at least one sensor to transmit a signal representative of the measurement of said at least one sensor to said processor.

4. The vehicle of claim **1**, wherein the state of the vehicle diagnosed by said processor includes angular motion of the vehicle.

5. The vehicle of claim **1**, wherein the state of the vehicle diagnosed by said processor includes a determination of a location of an impact between the vehicle and another object.

6. The vehicle of claim **5**, wherein said processor is structured and arranged to forecast the severity of the impact using the force/crush properties of the vehicle at the impact location and control the occupant restraint system based at least in part on the severity of the impact.

7. The vehicle of claim **1**, wherein at least one of said sensors is a weight sensor coupled to a seat in the vehicle for sensing the weight of an occupying item of the seat, said weight sensor being coupled to said processor and said processor controlling the occupant restraint system based on the state of the vehicle and the weight of the occupying item of the seat sensed by said weight sensor.

8. The vehicle of claim **1**, wherein said processor includes pattern recognition means for diagnosing the state of the vehicle.

9. The vehicle of claim **1**, further comprising a display coupled to said processor for displaying an indication of the state of the vehicle as diagnosed by said processor.

10. The vehicle of claim **1**, further comprising a warning device coupled to said processor for relaying a warning to an occupant of the vehicle relating to the state of the vehicle as diagnosed by said processor.

11. The vehicle of claim **1**, further comprising a transmission device coupled to said processor for transmitting a signal to a remote site relating to the state of the vehicle as diagnosed by said processor.

12. The vehicle of claim **1**, wherein the state of the vehicle includes angular acceleration, a plurality of said sensors comprising accelerometers such that said processor determines the angular acceleration of the vehicle based on the acceleration measured by said accelerometers.

13. The vehicle of claim **1**, wherein at least one of said sensors comprises a high dynamic range accelerometer.

14. The vehicle of claim **1**, wherein at least one of said sensors comprises a gyroscope including a surface acoustic

wave resonator which applies standing waves on a piezoelectric substrate.

15. In a motor vehicle, a control system for controlling an occupant restraint system, comprising:

a plurality of sensors mounted at different locations on the vehicle, each of said sensors providing a measurement related to a state of said sensor or a measurement related to a state of the mounting location; and

a processor coupled to said sensors and arranged to diagnose the state of the vehicle based on the measurements of said sensors,

said processor being arranged to control the occupant restraint system based at least in part on the diagnosed state of the vehicle,

at least two of said sensors each being a sensor selected from a group consisting of a single axis acceleration sensor, a double axis acceleration sensor, a triaxial acceleration sensor and a gyroscope.

16. In a motor vehicle, a control system for controlling an occupant restraint system, comprising:

a plurality of sensors mounted at different locations on the vehicle, each of said sensors providing a measurement related to a state of said sensor or a measurement related to a state of the mounting location; and

a processor coupled to said sensors and arranged to diagnose the state of the vehicle based on the measurements of said sensors, said processor including pattern recognition means for diagnosing the state of the vehicle and being arranged to control the occupant restraint system based at least in part on the diagnosed state of the vehicle.

17. In a motor vehicle, a control system for controlling a navigation system, comprising:

a plurality of sensors mounted at different locations on the vehicle, each of said sensors providing a measurement related to a state of said sensor or a measurement related to a state of the mounting location; and

a processor coupled to said sensors and arranged to diagnose the state of the vehicle based on the measurements of said sensors, the state of the vehicle diagnosed by said processor including angular motion of the vehicle whereby angular position or orientation are derivable from the angular motion,

said processor being arranged to control the navigation system based on the angular acceleration of the vehicle.

18. A method for controlling an occupant restraint system in a vehicle comprising the steps of:

mounting a plurality of electronic sensors at different locations on the vehicle;

measuring a state of the sensor or a state of the respective mounting location of the sensor;

diagnosing the state of the vehicle based on the measurements of the state of the sensors or the state of the mounting locations of the sensors, and

controlling the occupant restraint system based at least in part on the diagnosed state of the vehicle in an attempt to minimize injury to an occupant in the event of a crash.

19. The method of claim **18**, wherein the state of the sensor is the acceleration, angular motion, angular velocity or angular orientation of the sensor.

20. The method of claim **18**, wherein the state of the vehicle is diagnosed by a processor, further comprising the steps of:

providing at least one of the sensors with an RF (radio frequency) response unit;

mounting at least one RF interrogator device on the vehicle; and

transmitting signals via the at least one RF interrogator device to cause the RF response units of the at least one sensor to transmit a signal representative of the measurements of the at least one sensor to the processor.

21. The method of claim **18**, wherein the step of diagnosing the state of the vehicle comprises the step of determining whether the vehicle is stable or is about to rollover or skid.

22. The method of claim **18**, wherein the step of diagnosing the state of the vehicle comprises the step of determining a location of an impact between the vehicle and another object.

23. The method of claim **22**, further comprising the step of forecasting the severity of the impact using the force/crush properties of the vehicle at the impact location, the occupant restraint system being controlled based at least in part on the severity of the impact.

24. The method of claim **18**, further comprising the step of sensing the weight of an occupying item of a seat of the vehicle, the occupant restraint system being controlled based at least in part on the weight of the occupying item of the seat.

25. The method of claim **18**, further comprising the step of displaying an indication of the state of the vehicle.

26. The method of claim **18**, further comprising the step of relaying a warning to an occupant of the vehicle relating to the state of the vehicle.

27. The method of claim **18**, further comprising the step of transmitting a signal to a remote site relating to the state of the vehicle.

28. The method of claim **18**, wherein a plurality of the sensors comprise accelerometers, the step of diagnosing the state of the vehicle comprises the step of determining angular motion of the vehicle based on the acceleration measured by said accelerometers.

29. A method for controlling an occupant restraint system in a vehicle comprising the steps of:

mounting a plurality of electronic sensors at different locations on the vehicle;

measuring a state of the sensor which is the acceleration, angular acceleration, angular velocity or angular orientation of the sensor;

diagnosing the state of the vehicle based on the measurements of the state of the sensors or the state of the mounting locations of the sensors, and

controlling the occupant restraint system based at least in part on the diagnosed state of the vehicle in an attempt to minimize injury to an occupant in the event of a crash.

30. A method for controlling an occupant restraint system in a vehicle comprising the steps of:

mounting a plurality of electronic acceleration sensors at different locations on the vehicle;

measuring a state of the sensor or a state of the respective mounting location of the sensor;

diagnosing the state of the vehicle based on the measurements of the state of the sensors or the state of the

mounting locations of the sensors, the step of diagnosing the state of the vehicle comprises the step of determining angular motion of the vehicle based on the acceleration measured by said acceleration sensors; and

controlling the occupant restraint system based at least in part on the diagnosed state of the vehicle in an attempt to minimize injury to an occupant in the event of a crash.

31. A method for controlling a navigation system in a vehicle comprising the steps of:

mounting a plurality of sensors at different locations on the vehicle;

measuring a state of the sensor or a state of the respective mounting location of the sensor;

diagnosing the state of the vehicle based on the measurements of the state of the sensors or the state of the mounting locations of the sensors, the step of diagnosing the state of the vehicle comprising the step of determining angular motion of the vehicle whereby angular position or orientation are derivable from the angular motion; and

controlling the navigation system based at least in part on the diagnosed state of the vehicle in an attempt to minimize injury to an occupant in the event of a crash, the step of controlling the at least one part comprising the controlling the navigation system based on the angular acceleration of the vehicle.

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